

# SUSY & SUGRA SIGNATURES AT HADRON COLLIDERS<sup>1</sup>

D.P. Roy

Tata Institute of Fundamental Research,  
Homi Bhabha Road, Mumbai 400 005, India

**Abstract:** After a brief introduction to SUSY I discuss the missing- $p_T$  signature for superparticles from  $R$ -parity conservation and the multilepton signature, which follows from their cascade decay. The GUT and SUGRA constraints on the SUSY mass parameters are discussed along with the resulting SUSY signals at LHC. Finally I consider the effect of relaxing the SUGRA constraint on these signals.

**Why SUSY? (Hierarchy Problem):** Assuming the Higgs mechanism of electroweak symmetry breaking one is faced with the hierarchy problem, i.e. how to peg down the Higgs scalar in the desired mass range of  $\sim 10^2$  GeV. This is because the scalar masses are known to have quadratically divergent quantum corrections from radiative loops involving e.g. scalars or fermions. These would push the output scalar mass to the cut-off scale of the SM, i.e. the GUT scale ( $10^{16}$  GeV) or the Planck scale ( $10^{19}$  GeV). The desired mass range of  $\sim 10^2$  GeV is clearly tiny compared to these scales. The underlying reason for the quadratic divergence is that the scalar masses are not protected by any symmetry unlike the fermion and the gauge boson masses, which are protected by chiral symmetry and gauge symmetry. Of course it was this very property of the scalar mass that was exploited to give masses to the fermions and gauge bosons in the first place. Therefore it can not be simply wished away.

The most attractive solution to this problem is provided by supersymmetry (SUSY), a symmetry between fermions and bosons [1]. It predicts the quarks and leptons to have scalar superpartners called squarks and sleptons ( $\tilde{q}, \tilde{\ell}$ ), and the gauge bosons to have fermionic superpartners called gauginos ( $\tilde{g}, \tilde{\gamma}, \tilde{W}, \tilde{Z}$ ). In the minimal supersymmetric standard model (MSSM) one needs two Higgs doublets  $H_{1,2}$ , with opposite hypercharge  $Y = \pm 1$ , to give masses to the up and down type quarks. The ratio of their vevs is denoted by  $\tan \beta$ . The corresponding fermionic superpartners are called Higgsinos ( $\tilde{H}_{1,2}$ ). The opposite hypercharge of these two sets of fermions ensures anomaly cancellation.

SUSY ensures that the quadratically divergent quantum corrections from scalar and fermion loops are cancelled by the loop contributions from the corresponding super partners. Thus the Higgs masses can be kept in the desired range of  $\sim 10^2$  GeV. However this implies two important constraints on SUSY breaking.

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- i) SUSY can be broken in masses but not in couplings (soft breaking), so that the coefficients of the cancelling contributions remain equal and opposite.
- ii) The size of SUSY breaking in masses is  $\sim 10^2$  GeV, so that the size of the remainder remains within this range. Thus the superpartners of the SM particles are also expected to lie in the mass range of  $\sim 10^2$  GeV, going upto 1000 GeV.

***R*-Parity Conservation & the Missing- $p_T$  Signature:** I shall concentrate on the standard *R*-Parity conserving SUSY model. Let me start therefore with a brief discussion of *R*-parity. The presence of scalar quarks in SUSY can lead to baryon and lepton number violating interactions of the type  $ud \rightarrow \tilde{s}$  and  $\tilde{s} \rightarrow e^+ \bar{u}$ , i.e.

$$ud \xrightarrow{\tilde{s}} e^+ \bar{u}. \quad (1)$$

Moreover adding a spectator  $u$  quark to both sides one sees that this can lead to a catastrophic proton decay, i.e.

$$p(ud) \xrightarrow{\tilde{s}} e^+ \pi^0 (\bar{u}u). \quad (2)$$

Since the superparticle masses are assumed to be of the order  $M_W$  for solving the hierarchy problem, this would imply a proton life time similar to the typical weak decay time of  $\sim 10^{-8}$  sec! The best way to avoid this catastrophic proton decay is via *R*-parity conservation, where

$$R = (-1)^{3B+L+2S} \quad (3)$$

is defined to be +1 for the SM particles and  $-1$  for their superpartners, since they differ by 1/2 unit of spin  $S$ . It automatically ensures  $L$  and  $B$  conservation by preventing single emission (absorption) of superparticle.

Thus *R*-conservation implies that (i) superparticles are produced in pair and (ii) the lightest superparticle (LSP) is stable. Astrophysical evidences against such a stable particle carrying colour or electric charge imply that the LSP is either sneutrino  $\tilde{\nu}$  or photino  $\tilde{\gamma}$  (or in general the lightest neutralino). The latter alternative is favoured by the present SUSY models. In either case the LSP is expected to have only weak interaction with ordinary matter like the neutrino, since e.g.

$$\tilde{\gamma} q \xrightarrow{\tilde{q}} q \tilde{\gamma} \quad \text{and} \quad \nu q \xrightarrow{W} e q' \quad (4)$$

have both electroweak couplings and  $M_{\tilde{q}} \sim M_W$ . This makes the LSP an ideal candidate for the cold dark matter. It also implies that the LSP would leave the normal detectors without a trace like the neutrino. The resulting imbalance in the visible momentum constitutes the canonical missing transverse-momentum ( $\cancel{p}_T$ ) signature for superparticle production at hadron colliders. It is also called the missing transverse-energy ( $\cancel{E}_T$ ) as it is often measured as a vector sum of the calorimetric energy deposits in the transverse plane.

The main processes of superparticle production at hadron colliders are the QCD processes of quark-antiquark and gluon-gluon fusion [2]

$$q\bar{q}, gg \longrightarrow \tilde{q}\tilde{\bar{q}}(\tilde{g}\tilde{g}). \quad (5)$$

The NLO corrections can increase these cross-sections by 15 – 20% [3]. The simplest decay processes for the produced squarks and gluinos are

$$\tilde{q} \rightarrow q\tilde{\gamma}, \quad \tilde{g} \rightarrow q\bar{q}\tilde{\gamma}. \quad (6)$$

Convoluting these with the pair production cross-sections (5) gives the simplest jets +  $\cancel{p}_T$  signature for squark/gluino production, which were adequate for the early searches for relatively light squarks and gluinos.

**Cascade Decay and the Multilepton Signature:** Over the mass range of current interest ( $\geq 100$  GeV) however the cascade decays of squark and gluino into the LSP via the heavier chargino/neutralino states are expected to dominate over the direct decays (6). This is both good news and bad news. On the one hand the cascade decay degrades the missing- $p_T$  of the canonical jets +  $\cancel{p}_T$  signature. But on the other hand it gives a new multilepton signature via the leptonic decays of these chargino/neutralino states. It may be noted here that one gets a mass limit of

$$M_{\tilde{q},\tilde{g}} > 180 \text{ GeV} \quad (7)$$

from the Tevatron data using either of the two signatures [4].

The cascade decay is described in terms of the  $SU(2) \times U(1)$  gauginos  $\tilde{W}^{\pm,0}, \tilde{B}^0$  along with the Higgsinos  $\tilde{H}^{\pm}, \tilde{H}_1^0$  and  $\tilde{H}_2^0$ . The  $\tilde{B}$  and  $\tilde{W}$  masses are denoted by  $M_1$  and  $M_2$  respectively while the Higgsino masses are functions of the supersymmetric Higgsino mass parameter  $\mu$  and  $\tan\beta$ . The charged and the neutral gauginos will mix with the corresponding Higgsinos to give the physical chargino  $\chi_{1,2}^{\pm}$  and neutralino  $\chi_{1,2,3,4}^0$  states. Their masses and compositions can be found by diagonalising the corresponding mass matrices, i.e.

$$M_C = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin\beta \\ \sqrt{2}M_W \cos\beta & \mu \end{pmatrix},$$

$$M_N = \begin{pmatrix} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\mu \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & -\mu & 0 \end{pmatrix}. \quad (8)$$

Thus the cascade decay involves a host of new parameters ( $M_1, M_2, \mu$  and  $\tan\beta$ ) along with the parent squark or gluino mass. Consequently one looks for theoretical constraints relating these parameters to one another.

**The GUT and SUGRA Constraints:** The most important theoretical constraint comes from GUT, which implies the famous unification of  $SU(3) \times SU(2) \times U(1)$  gauge couplings

(Fig. 1). It also implies the unification of the corresponding gaugino masses at the GUT scale, since they evolve exactly like the gauge couplings, i.e.

$$M_i(\mu) = m_{1/2}\alpha_i(\mu)/\alpha_i(M_G). \quad (9)$$

Thus one sees from the Fig. 1 [5], that at the low-energy scale,  $\mu \sim M_W$ ,

$$\begin{aligned} M_2 &= m_{1/2}\alpha_2/\alpha_2(M_G) \simeq m_{1/2}, \\ M_1 &= M_2(\alpha_1/\alpha_2) \simeq M_2/2, \\ M_{\tilde{g}} &\equiv M_3 = M_2(\alpha_3/\alpha_2) \simeq 3M_2. \end{aligned} \quad (10)$$

Unlike the gaugino mass unification, the unification of scalar masses at  $M_G$  does not follow from any GUT symmetry but from the minimal SUGRA model. As per this model, SUSY is broken in the hidden sector and its effect communicated to the observable sector via gravitational interaction. Since this interaction is colour and flavour blind, it leads to a common soft SUSY breaking mass for all the scalars

$$\mathcal{L}_{\text{soft}} = m_0^2(\tilde{\ell}_i^2 + \tilde{q}_i^2 + H_k^2) + \dots \quad (11)$$

In addition there is a supersymmetric contribution to the Higgs masses,  $\mu^2 H_k^2$ , following from the superpotential  $W = \mu H_1 H_2 + h_t Q H_2 U + h_b Q H_1 D + h_\tau L H_1 E$ . Thus the GUT scale unification of scalar masses is admittedly a model dependent assumption. Nonetheless it makes a remarkable prediction when evolved to low energy (Fig. 2) — i.e. one of Higgs scalar masses,  $M_{H_2}^2$ , is driven negative by the large top Yukawa coupling contribution  $h_t t\bar{t} H_2$  [6]. This is the famous radiative mechanism of electroweak symmetry breaking. Requiring this EWSB to occur at the right mass scale determines the magnitude of  $\mu$ , i.e.

$$|\mu| \sim (2-3)m_{1/2} \sim (2-3)M_2. \quad (12)$$

**SUGRA Signals at LHC:** It is clear from (8,10 and 12) that the lighter chargino and neutralino states in the SUGRA model are dominated by gaugino components,

$$\chi_{1,2}^\pm \simeq \tilde{W}^\pm, \tilde{H}^\pm; \chi_{1,2,\dots}^0 \simeq \tilde{B}, \tilde{W}^0, \dots \quad (13)$$

Moreover one expects only a modest effect from the mixing between the gaugino and Higgsino components and hence the relevant parameter,  $\tan\beta$ .

With the above systematics one can understand the essential features of cascade decay. For illustration I shall briefly discuss cascade decay of gluino for two representative gluino mass regions of interest to LHC.

i)  $M_{\tilde{g}} \simeq 300$  GeV: In this case the gluino decays into the light quarks

$$g \rightarrow \bar{q}q \left[ \tilde{B}(.2), \tilde{W}^0(.3), \tilde{W}^\pm(.5) \right], \quad q \neq t, \quad (14)$$

which have negligible Yukawa couplings. Thus the decay branching ratios are proportional to the squares of the respective gauge couplings as indicated in parantheses. Because of the smaller  $U(1)$  gauge coupling relative to the  $SU(2)$ , the direct decay into the LSP ( $\tilde{B}$ ) is small compared to cascade decay via the heavier ( $\tilde{W}$  dominated) chargino and neutralino states. The latter decay into the LSP via real or virtual  $W/Z$  emission,

$$\tilde{W}_0 \rightarrow Z\tilde{B} \rightarrow \ell^+\ell^-\tilde{B}(.06), \quad \tilde{W}^\pm \rightarrow W\tilde{B} \rightarrow \ell^\pm\nu\tilde{B}(.2), \quad (15)$$

whose leptonic branching ratios are indicated in parantheses. From (14) and (15) one can easily calculate the branching ratios of dilepton and trilepton states resulting from the decay of a gluino pair (5). In particular the dilepton final state via charginos has a branching ratio of 1%. Then the Majorana nature of  $\tilde{g}$  implies a distinctive like sign dilepton (LSD) signal with a BR of  $\sim 1/2\%$ .

- ii)  $\tilde{M}_{\tilde{g}} \gtrsim 500$  GeV: In this case the large top Yukawa coupling implies a significant decay rate via

$$\tilde{g} \rightarrow t\bar{b}\tilde{H}^-, \quad (16)$$

where both  $t$  and  $\tilde{H}^-$  can contribute to the leptonic final state via

$$t \rightarrow bW^+ \rightarrow b\ell^+\nu(.2), \quad \tilde{H}^- \rightarrow W^-\tilde{B} \rightarrow \ell^-\nu\tilde{B}(.2). \quad (17)$$

Consequently the BR of the LSD signal from the decay of the gluino pair is expected to go up to 2 – 3%.

Fig. 3 shows the expected LSD signal from gluino pair production at LHC for  $M_{\tilde{g}} = 300$  and 800 GeV along with the background [7]. The latter comes from  $t\bar{t}$  via cascade decay (long dashed) or charge misidentification (dots). Note that the signal is accompanied by a much larger  $p_T$  compared to the background because of the LSPs. This can be used to effectively suppress the background while retaining about 1/2 of the signal. Consequently one can search for a gluino upto at least 800 GeV at the low luminosity ( $10fb^{-1}$ ) run of LHC, going upto 1200 GeV at the high luminosity ( $100fb^{-1}$ ).

Fig. 4 shows the size of the canonical  $p_T$ + jets signal against gluino mass for two cases –  $M_{\tilde{g}} \ll M_{\tilde{q}}$  (triangles) and  $M_{\tilde{g}} \simeq M_{\tilde{q}}$  (squares) [8]. The background line shown also corresponds to  $5\sqrt{B}$  for the LHC luminosity of  $10fb^{-1}$ . Thus one expects a  $5\sigma$  discovery limit of at least upto  $M_{\tilde{g}} = 1300$  GeV from this signal. Finally Fig. 5, shows the CMS simulation [9] for the  $5\sigma$  discovery limits from the various leptonic channels in the plane of  $m_0 - m_{1/2}$ , the common scalar and gaugino masses at the GUT scale. The corresponding squark and gluino mass contours are also shown. As we see from this figure, it will be possible to extend the squark and gluino searches at LHC well into the TeV region.

**Relaxing the SUGRA Constraint:** As mentioned earlier, the GUT scale unification of scalar masses (11) is highly model dependent. Even in SUGRA model it can be broken by nonminimal contributions to  $\mathcal{L}_{\text{soft}}$ . Alternatively, starting from the minimal SUGRA constraint (11) at the Plank scale one can get large splitting between the soft masses of  $\tilde{q}, \tilde{\ell}$  and the Higgs scalars at the GUT scale, since they follow different evolution equations [10]. Therefore it is important to probe for the SUSY signal by relaxing the SUGRA constraints

(11,12). Its main effect on the gluino signature comes from floating the  $\mu$  parameter and in particular allowing the light Higgsino region,

$$|\mu| \lesssim M_{1,2}. \quad (18)$$

Here one expects a near degeneracy between the  $\chi_1^0$  and  $\chi_2^0$  masses ( $\simeq |\mu|$ ) in contrast to a factor of 2 difference between them in the SUGRA case (12,13). Thus one expects very different event kinematics in the two regions. Moreover the most important gluino decays in the light Higgsino region are

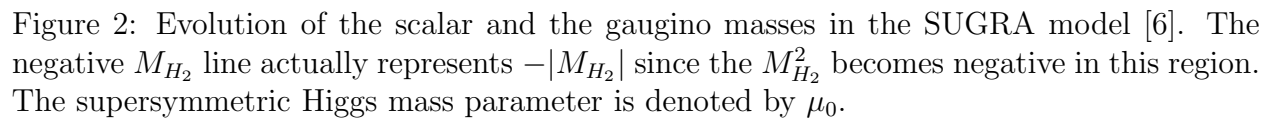
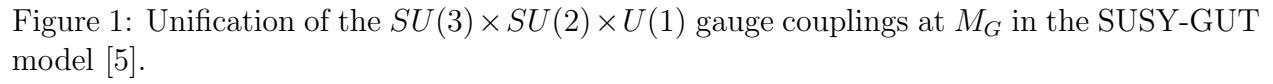
$$\tilde{g} \rightarrow t\bar{b}\chi_1^\pm, t\bar{t}\chi_1^0 \quad (19)$$

which result in a significantly larger LSD signal compared to the SUGRA case [7].

It should be noted that the SUSY search at LEP has been carried out over the full  $\mu - M_2$  plane. In contrast the investigations for hadron colliders have largely been restricted to the region of SUGRA constraint (12), i.e. the light gaugino region (13). This was partly a matter of expediency for Tevatron, since in the complimentary region of light Higgsino (18) the LEP search via  $Z \rightarrow \chi_1^0\chi_1^0$  had already pre-empted the range  $M_2 \rightarrow 100$  GeV (i.e.  $M_{\tilde{g}} \rightarrow 300$  GeV). Nonetheless it is desirable to cover this range via the direct gluino search at Tevatron. There is of course no LEP constraint for the  $M_{\tilde{g}}$  range of interest to LHC. Therefore the SUSY simulations for LHC should be extended to cover at least some representative values of  $\mu$  in the  $|\mu| \lesssim M_{1,2}$  region [7].

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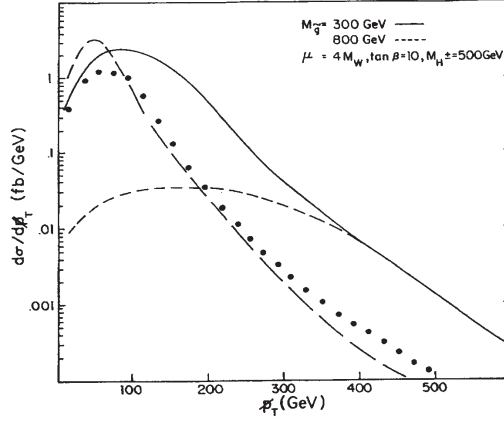


Figure 3: The expected size of the LSD signals for 300 and 800 GeV gluino production at LHC are shown against the accompanying missing- $p_T$ . The real and fake LSD backgrounds from  $t\bar{t}$  production are shown by long dashed and dotted lines respectively [7].

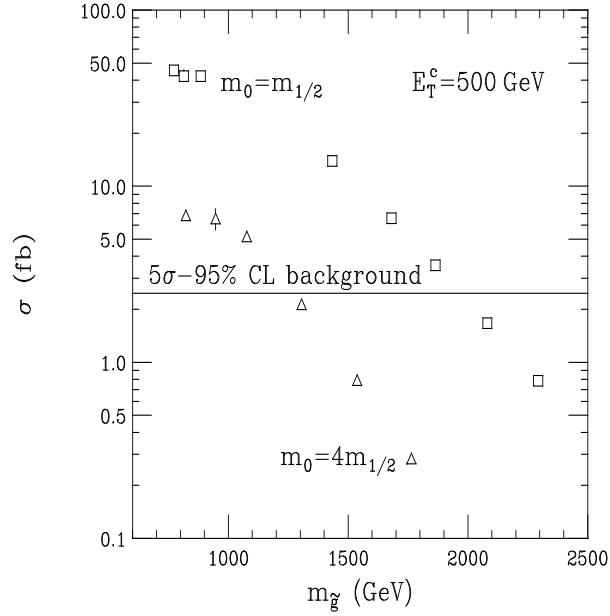


Figure 4: The expected gluino signals at LHC from jets + missing- $E_T$  channel are shown for  $M_{\tilde{g}} \simeq M_{\tilde{q}}$  (squares) and  $M_{\tilde{g}} \ll M_{\tilde{q}}$  (triangles). The 95% CL background shown also corresponds to  $5\sqrt{B}$  for the LHC luminosity of  $10fb^{-1}$  [8].



Explorable domain of  $m_0$   $m_{1/2}$  parameter space  
with  $100 \text{ fb}^{-1}$  in  $\tilde{q}, \tilde{g}$  searches  
in  $n$  leptons +  $E_t^{\text{miss}} + > 2$  jets final states

SUGRA - MSSM,  $\tan \beta \geq 2$ ,  $A_0 = 0$ ,  $\mu < 0$   
5  $\sigma$  contours

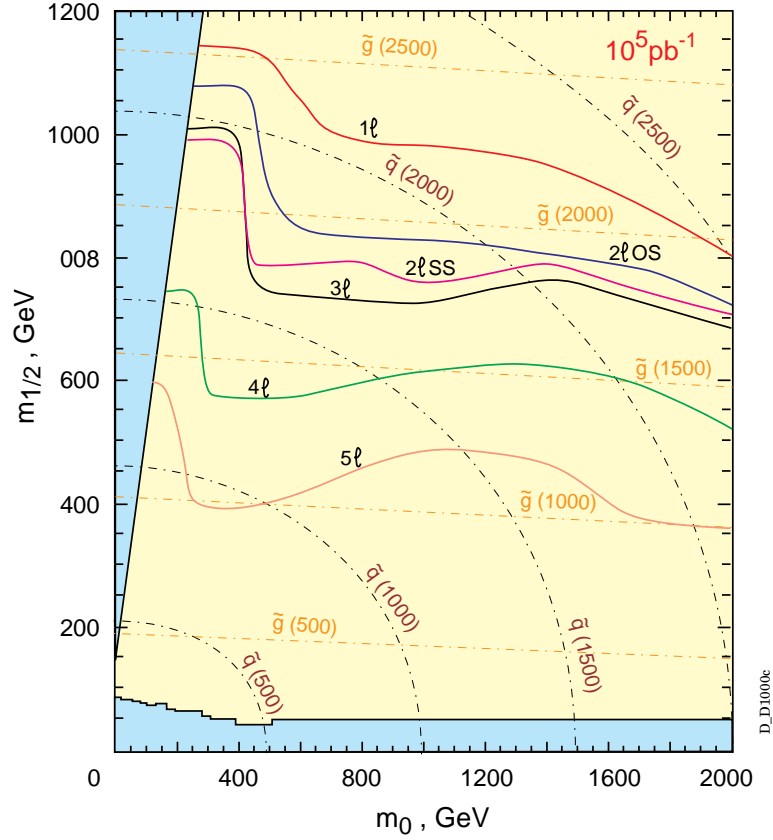


Figure 5: The SUSY discovery limits of various leptonic channels at LHC, where  $2lOS$  and  $2lSS$  denote opposite sign and same sign dileptons [9].